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Autonomous Aerial Sensors for Wind Power Meteorology

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Abstract: This poster describes a new approach for measurements in wind power meteorology using small unmanned flying platforms. During a week of flying a lighter-than-air vehicle, two small electrically powered aeroplanes and a larger helicopter at the Risø test station at Høvsøre, we will compare wind speed measurements with fixed mast and LIDAR measurements, investigate optimal flight patterns for each measurement task, and measure other interesting meteorological features like the air-sea boundary in the vicinity of the wind farm. If successful, the planes could be used in such diverse areas as the investigation of turbulence structure in wakes, for work on the comparison between line measurements and fixed measurement relating to Taylor's Hypothesis, for more general meteorology like the investigation of the air-sea boundary, the top of the boundary layer or the night-time stability structure. Additional services for the wind power industry could include inspection of wings or other difficult to access parts. In order to prepare the measurement campaign, a workshop is held, soliciting input from various communities.

Introduction

Large-scale wind farms, especially offshore, need an optimisation between installed wind power density and the losses in the wind farm due to wake effects between the turbines. While the wake structure behind single wind turbines onshore is fairly well understood, there are different problems offshore, thought to be due mainly to the low turbulence. Good measurements of the wake and wake structure are not easy to come by, as the use of a met mast is static and expensive, while the use of remote sensing instruments either needs significant access to the turbine to mount an instrument, or is complicated to use on a ship due to the ship's own movement. In any case, a good LIDAR or SODAR will cost many tens of thousands of euros.

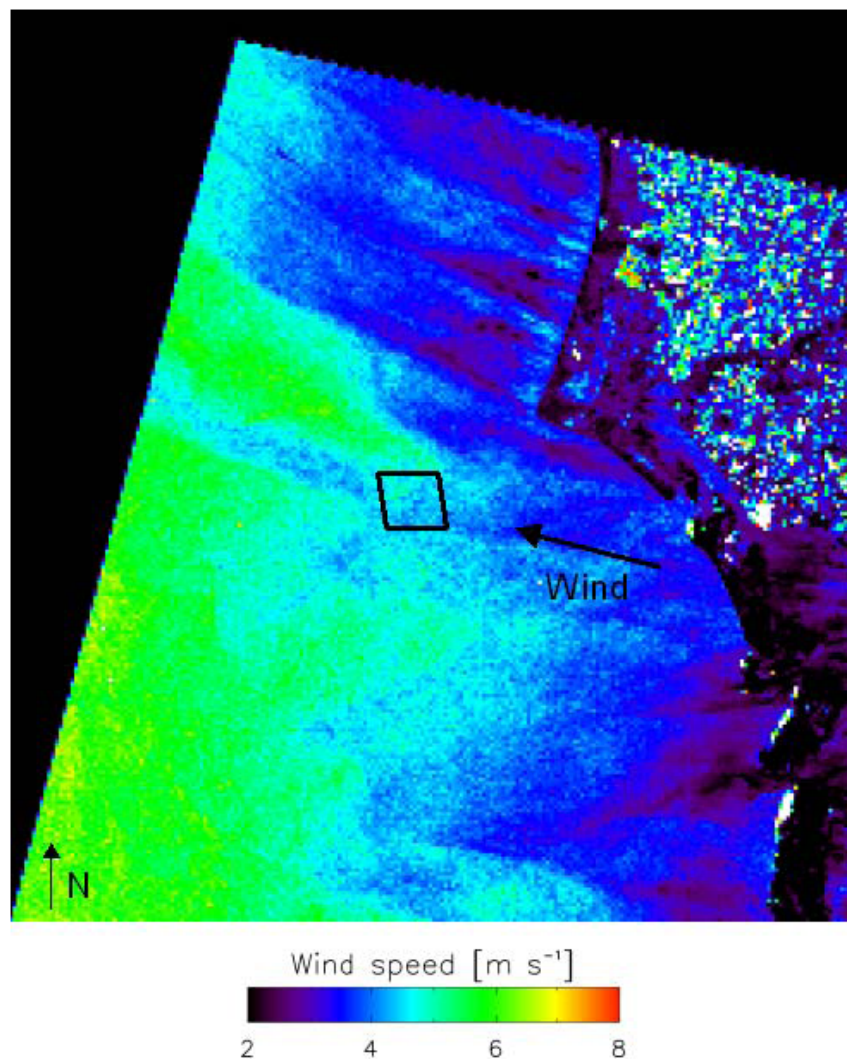
Another current problem in wind energy is the coming generation of wind turbines in the 10-12 MW class, with tip heights of over 200 m. Very few measurement masts exist to verify our knowledge of atmospheric physics – all that is known is that the boundary layer description we used so far is not valid any more.

Here, automated Unmanned Aerial Vehicles (UAVs) could be used as either an extension of current high masts or to build a network of very high 'masts' in a region of complex terrain or coastal flow conditions. In comparison to a multitude of high masts (a mast of 100m height plus instruments can be about 200.000 euros), UAVs could be quite cost-effective.

In order to test this assumption and to test the limits of UAVs for wind power meteorology, this project assembles four different UAVs from four participating groups. Risø will build a lighter-than-air kite with a long tether, Bergen University flies a derivative of the Funjet, a pusher airplane of 580g total weight, the University of Tübingen in conjunction with TU Braunschweig flies the

Carolo, a 2m wide two prop model with a pitot tube on the nose, and Aalborg University will use a helicopter equipped with a sonic anemometer. All those platforms will be flown during one week, probably at the Danish national test station for large wind turbines at Høvsøre. The site is strongly instrumented, with 6 masts above 100m height, one even reaching up to 167m. The comparison of wind speed measurements from planes and fixed masts should give an indication of the accuracy of the measured wind field.

This project should be seen as the precursor to a larger development effort. At this stage, we need to map the state-of-the-art and its applicability to wind power meteorology. The next project should then delve into the actual development of dedicated aerial sensor packages for wind power, taking into account the lessons learned from this quick exercise.



Wind field at Horns Rev based on ERS-2 SAR image from 25 February 2003. The black trapezoid indicates the wind farm. For scaling, the total wind farm width is ~ 5 km. The wind direction is 110° from the meteorological mast. A reduction of wind speed is seen downstream of the wind farm. Note also the strong shadowing effects of the land. Source: [Christiansen 2007]

Therefore, we propose three main work packages. WP1 should be the mapping of the state-of-the-art and expected developments in the fields of aerial platforms, including model airplanes, helicopters, quadrocopters, kites, balloons, and any other technology which can transport a sensor package aloft and keep it there for some time. A second part of this WP will deal with the sensors to

be mounted on the aerial platforms. This work package will be based strongly on the similar effort done in the COST action ES0802 “Unmanned aerial systems (UAS) in atmospheric research”, of which Jochen Reuder of Bergen University is the leader. WP2 will then look at how to use the incoming data in wind power meteorology. Airplanes for example will probably do sampling along a line – how can we use the wind profile along a line for understanding more of the atmosphere, and how can we compare this to the large body of understanding 10-min mean values of fixed sensors? The main part of this activity is going to be a workshop for wind power meteorology stakeholders. Based on the results of WP2, WP3 is the experimental measurement campaign at Høvsøre, comparing performance of different aerial sensors directly for the study of the atmospheric boundary layer.



Figure 1: The test station at Høvsøre. The five wind turbines are in the foreground, the smaller met masts are at the left of each turbine.

Existing Parts

At the time being, some sensors, controllers, airframes / kites / balloons and ground stations are available and in some cases even as open-source. One of the tasks of the project is to write a report on the existing platforms and sensors that exist on the market and on corresponding ongoing and intended research and development activities. Most of the available wind and in particular turbulence measurement systems are too large and too heavy, at least for the smallest UAS systems as SUMO. As low weight and corresponding low impact energies in case of a collision with the wind turbine structures is desirable, the focus will be set on efforts to miniaturize the corresponding sensors and data acquisition systems.

Of the aerial vehicles intended to fly in this project, the University of Bergen has developed the Small Unmanned Meteorological Observer (SUMO) originally branded as “recoverable radiosonde” for atmospheric boundary layer research (Figure 2). The SUMO platform is based on

the Funjet, a cheap model airplane. The customisations of the plane are numerous sensors, such as temperature, humidity and pressure. The total weight in flyaway conditions is 580g. In this configuration, the plane can stay about 25 minutes in the air. With a maximum ascent rate of 15 m/s and an average ascent rate of 7-10 m/s, it can reach 3.5 (up to 6) km maximum altitude above ground. The range of air speeds is from 8 to 35 m/s, with an average of 12-18 m/s. SUMO has now been operated during 7 measurement campaigns on Iceland, Germany, Norway and on and around Spitsbergen, partly even from the helicopter deck of the Norwegian Coast Guard vessel KV Svalbard [Reuder et al. 2008a] and performed a total number of more than 400 scientific flight missions.

Mavionics of Braunschweig has developed a somewhat larger plane offshore in Germany [Bange and van den Kroonenberg 2008] and assembled 100Hz wind data, the Carolo. However, the company has gone out of business during the financial crisis. A variant of the Carolo named M²AV will be flown through Tübingen University.



Figure 2: The autonomous SUMO airframe and laptop used as ground control station. The length is 75cm, the wing span is 80cm.



Figure 3: Operation of the SUMO system during a measurement campaign on Svalbard in spring 2010, dedicated to the investigation of the stable polar atmospheric boundary layer and orographic flow modification.

The automatically operating Meteorological Mini Aerial Vehicle (M²AV) [Spieß et al. 2007; van den Kroonenberg et al. 2008] was developed at the Institute of Aerospace Systems (ILR), Technical University of Braunschweig. It is based on the unmanned 'Carolo T200' aircraft as carrier system with a wingspan of 2 m. The maximum take-off weight is 6 kg, including payload of 1.5 kg [Spieß et al., 2007].

The aircraft is hand-launched and operates then under the control of a board computer. The autopilot developed at the ILR is programmed prior to the flight, and the waypoints in three dimensions can be updated during the mission by a telemetry link from the ground-based station. The M²AV endurance is about 60 minutes with a cruising speed of 22 m/s. The meteorological, navigation and attitude data is stored on board at 100 Hz resolution. Flight information can be transmitted to the ground station to allow monitoring of the state of the mission. The turbulence payload of the M²AV was developed by the Airborne Geoscience group of the ILR. The largest part of this group moved to Tübingen University, recently.

The instrumentation for temperature measurement comprises two sensors with different characteristics. One is a Vaisala HMP 50 resistance thermometer sensor with high accuracy but slow response time (in flight about 1s). The second sensor is a thermocouple (type K) with a poor long-term stability but fast response time (30 Hz) for turbulence measurements. The signals of the two sensors are joint using a complementary filter with an overall temporal resolution of 30 Hz, a temperature resolution of about 0.01 K and an absolute accuracy of better than 0.5 K.

The same HMP 50 provides air humidity measurements (Vaisala Humicap). The sensor is a rather slow sensor but achieves a good accuracy (1-2 % relative humidity) over the temperature range of interest for the airborne missions.

The wind vector in the airframe coordinate system is measured by a five-hole probe (FHP) with a mass of only 22 g and a diameter of 6 mm. The FHP was developed and manufactured by the Institute of Fluid Dynamics, TU Braunschweig. It provides the angle of attack and sideslip in the range of -20° to +20° with 0.1° resolution due to calibration. The static pressure is measured via four extra holes at the side of the probe. For the calculation of the wind vector, the attitude of the aircraft is needed in high precision. This is achieved by a three dimensional GPS attitude measurement system. Additionally to the implemented autopilot hardware including an inertial measurement unit (IMU) with accelerometers and gyros, an extra IMU and GPS system is integrated in the meteorological data acquisition unit. During data post processing, the GPS and IMU data are merged using a complementary Kalman filter.

With its overall sampling rate of 100 Hz (except humidity) and effective anti-aliasing filtering at 33 Hz the spatial resolution of M²AV turbulence measurements (at typical 22 m/s airspeed) is in the sub-meter range. During vertical profiles (at a typical climb rate of 3 m/s) a vertical resolution of 10 cm can be achieved.

In 2005, the first scientific mission of the automatically operating unmanned turbulence probe M²AV [Spieß et al. 2007; van den Kroonenberg et al. 2008] was performed during the LAUNCH campaign near Lindenberg, followed by the first application of scientific UAV in Antarctica (during a 14 month stay at British Antarctic Survey station Halley). Latest M²AV missions focused on the in situ measurement of the turbulent structure parameter, the vertical probing of the convective ABL and morning transition [Bange et al. 2009; Martin et al. 2010a], and the first measurement of turbulent fluxes with small UAV [Martin and Bange 2009; Martin et al. 2010b].



Figure 4: The M²AV flying next to the meteorological tower of the German Weather Service near Lindenberg in 2009.

AAU has been flying autonomous helicopters for a couple of years, and therefore all necessary ground equipment, computers, telemetry modules, and various tools for test flights are available. Further, AAU currently has two other research projects of interest to this proposal; one which also employs the Vario XLC helicopter with the same autopilot; and one project which aims at controlling a (larger) helicopter in presence of strong and turbulent winds, and therefore employs various wind sensors onboard the helicopter. For this project, AAU has acquired and equipped the Vario XLC helicopter with a maximum take-off weight of 32 kg, of which 6 kg is payload. This allows mounting a full-blown single board PC and an R. M Young 8100 sonic anemometer on the tail. This way, the helicopter has to fly backwards or sideways to keep the anemometer out of the downwash, but the control system of the helicopter is able to do it safely, even though the flight envelope is somewhat reduced.

Risø DTU has bought the SkyDoc Lighter-than-Air (LTA) system from Floatograph. The system will be equipped with wind sensors and other sensors using the DELTA data acquisition system described below.

Piperas [Piperas 2010] has investigated the dynamical properties of the LTA system exposed to actual wind as measured at Høvsøre. Using 20-Herz Sonic data from various height levels, a model of the SkyDoc has been set up. The preliminary results show that the dynamic stability of the platform is very high, and the horizontal and vertical movement is quite limited and promising for the planned campaigns. A plot of the preliminary simulation displacements of the LTA system for flying at 100m above ground is shown in Figure 5. It can be seen that the LTA system is quite stable in the air, with quite small horizontal or vertical deviations.



Figure 5: The Vario XLC helicopter employed by Aalborg University (sensor and onboard computer is not mounted in these photos).



Figure 6: The SkyDoc Lighter-Than-Air system launched from a winch on a trailer, and a picture of a typical meteorological payload. Pictures from floatograph.com.

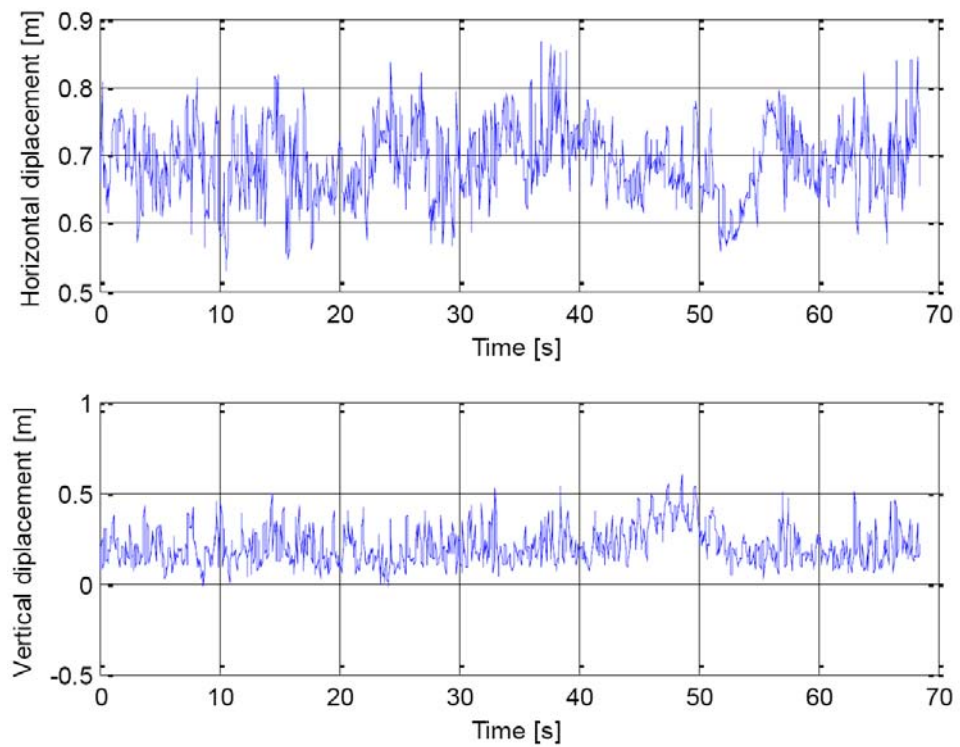


Figure 7: The calculated horizontal and vertical movement of the LTA platform.

The data acquisition system which enables capturing ensembles of velocity, pressure (dynamic & static), and temperature etc., is put as payload and serves as input to the control board.

One of the practical problems in this field is to keep the payload per unit of energy consumption as low as possible, for a given size of platform. The data capture of many parameters is for this reason to be small in volume, weight and power consumption. To accomplish this a leading Danish industry player in electronic systems will provide a precise, light-weight, rugged and non-expensive nano-synchronisation technology data acquisition unit. Nano-synchronisation means that all units distributed over the area to measure are synchronised down to an accuracy of 200 nanoseconds and know their exact position due to the built-in GPS system. With this technology monitored signals at different positions do not suffer of time delays or – lags. A precise positioning is also needed; therefore it is suggested to bring in the dual-frequency GPS technology with spin-off possibilities to the industry.

By providing precision time and position stamping of data, several advantages are obtained:

- Data may be acquired at widely separated locations, such as on several UAVs and instrumentation masts, and later be merged to a highly accurate, synchronised timebase. This removes the need for real time experiment-wide telemetry systems, and also gives a much more accurate time stamping.
- Wind Turbine control signals, wing tip position, and other real time data can also be time stamped using nano-synchronization, thus giving a well-determined view of all events. The resulting data set has virtually perfect time/position integrity, hence cause/effect relationships can be computed with high confidence.
- The nano-synchronized architecture is scalable to any number of transducers and measurement points. Since data are logged to flash memory in each data acquisition device separately, there are no practical transmission bandwidth constraints, and high-channel count data can be merged perfectly after the conclusion of the experiment.
- For high channel count systems, there is no single point of failure, hence reliability is potentially much higher than for systems with real time telemetry.

Workshop

In the summer, we will organise a workshop as preparation for the flights later this year. We would like to get input on three main topics: wind speed measurements, wind power meteorological questions and flight related issues.

The first topic is mainly the question of how to derive good wind speed measurements from the devices, and to what accuracy those can be measured. With a Pitot tube, turbulence can be measured up to 100 or 200Hz, so spectra of turbulence up to the inertial sub-range are an option. What the sonic can do on the helicopter, and how contaminated the measurements are from the helicopter movements is another point for investigation. Scientifically quite interesting is the question of how to compare measurements along a flight path with measurements from a fixed mast. This leads to the limits or extensions to Taylors hypothesis, which essentially relates spatial wind patterns to time-based measurements. However, the cornerstone of wind power meteorology is the 10-min mean wind speed. How this can be achieved reliably, is an open question for a moving platform. In this sense, even the movements of the tethered LTA system needs to be verified.

Secondly, once the tools are available, which questions would we like to find answers to? Details of the wake structure, including multiple wakes offshore, are a logical candidate. The fine structure of vortex near the tip of the blade is another logical field. For a more generic meteorology investigation, the development of internal boundary layers both from offshore to onshore flow and

the night-time stable layer are good candidates. Also the wind speeds in heights greater than typical meteorology masts or even lidars allow (above 200m) are interesting.

Another interesting investigation could be the variation of wind profile/wind shear with atmospheric stability, as the UAS also provide temperature and humidity information.

Finally, how to best employ the technology at hand is a final point of discussion. Which flight patterns are best for which investigation? For the wakes, a logical idea is to do “race tracks” in front and behind the turbine row in various heights. However, for the Pitot tube, the angle of attack where it measures reliably is limited to some 20 degrees off the main axis. Can the plane be flown across the wake structure, i.e. perpendicular to the incident wind, and still measure reliably? Can the plane do loopings in the wakes, and if yes, can the data be interpreted? How can a flight pattern be found to measure a 10-min average wind speed with the same accuracy as a fixed sensor on a mast, e.g. by flying circles around the anemometer? What is the advantage of being able to hover – can this be used for the 10-min average, or does it have other advantages? Can the Funjet be made to fly so slow into the wind as to also hover, or will it have to stand so much on its tail that gusts cannot be handled any more? Is the “standing on its tail” too battery consuming? A further complex of questions relates to safety. How close can the planes get to the turbines while staying safely in the air? The tip speed vortices are quite violent, so it should not be too close, but which distance is safe? How far away can the wake structure actually be resolved? Is loitering time an issue?

Conclusions

A project is described to compare various robotic options for aerial wind measurements. Two planes, a helicopter and a tethered balloon are compared during one week of flying on one of the best instrumented sites in the wind power industry. For comparison of the experimental campaign, a workshop is held to pull new ideas into the project.

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